Spotting in stars with a low level of activity, cloze to solar activity

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Data on the variability of the continuum optical emission are used for the first time to estimate the degree of spotting in stars similar to that of the sun. It is sown that the amount of spotting increases gradually from the sun to the highly spotted stars for which Alekseev and Gershberg constructed the zonal model for the distributions of spots. A close relationship is found between spotting and the power of the x-ray emission from the stars with widely varying levels of activity

Keywords: stars spots, stellar coronae, solar-type stars

1. Introduction

The optical photometric observations of red dwarf stars regularly made at various observations since the beginning of the 1950's have revealed a low-amplitude quasiperiodic variability in the brightness of some of these stars owing to the presence of dark spots similar to sunspots on the surface of rotating stars. In turns out that the observed brightness variations are mainly related to the fact that the total spot area of the most highly spotted stars can be substantially greater than on the sun at the cycle maximum, approaching up to 40 % of the disc surface. Further observations have confirmed the existence of all the basic manifestations of solar-type activity on these stars, at the photospheric as well as at the chromospheric and coronal levels [1]. The chromospheric activity of stars has been studied for more than 40 years in a special program of regular observations of the H and K lines of Ca II, initially at Mount Wilson Observatory and then at the Smithsonian Observatory. Several of 111 stars from this so-called "HK-project" have regular cyclical variations in their chromospheric radiation with periods ranging mostly from 7 to 15 years [2]. The stars have been divided into groups based on the characteristics of their long-term brightness variations and how distinctly the cycles are expressed [2].

The launching of the High Astrophysical Observatory HEAO-2 in 1978 triggered extensive studies (in soft x-ray range) of the coronal activity of the stars of late-type spectral class.

The ROSAT satellite [3] has contributed the most data on the x-ray emission of these late-type stars. It turns out the best indicator of activity

in the outer atmospheres of stars in the ratio of the x-ray and bolometric luminosities, L_x/L_{bol}. This index is currently known for several hundred stars. The highest values of L_x/L_{bol} are found in stars of spectral class F with a high but irregular activity [4].

Recently several stars have been found to have cyclical variations in their soft x-ray fluxes, which confirms the existence of cyclical activity of the solar type stars of F,G, K and M spectral classes (photospheric, as well as chromospheric and coronal activity).

In this paper we limit ourselves only to examining quasistationary effects - the development of active regions, while neglecting flares, as such.

There are several ways or determining the relative area of spots from observations of long-term variability in the continuum or in the lines in the optical range. The most widespread methods are: constructing charts of surface nonuniformities (Doppler mapping or imaging) and the zonal model method. In most cases these two methods yield similar values for the spot areas on the surface of stars. Zonal model have been constructed for the stars whose photometric variability have been regularly observed at the CrAO (Crimean Astrophysical Observatory), and the area of the dark spots on their surfaces has been determined quite accurately [5,6]. This sample of stars includes several well known M-dwarfs (flare stars), as well as about a dozen K and G-stars. The amplitude of the rotational modulation in the optical continuum of these stars shows up distinctly, so that the amounts of spotting on their surfaces are substantial. We shall refer to this sample of stars as highly spotted.

In the course of a comparatively recent program of searching for planets, about one thousand stars with solar-type activity have been discovered [7]. These one thousand stars with observed emission in the H and K Ca II lines include a rather large number of stars for which the level of chromospheric activity is fairly low, similar to that of the sun. The spotting of the surface of these stars had to be determined in order to compare it with other characteristics of their activity. Photometric observations of some of these stars with a weak surface activity have been made over the last 20 years as a part of the "HK-project"[8].

In this paper we study the spottedness of late type stars that have different levels of activity and compare this data to other characteristics of their activity.

2.Estimating the spottedness of solar-type stars

The "HK-project" observational programm for studding the chromospheric activity of stars includes determination of the ratio of the radiative flux at the centers of the H and K emission lines of Ca II ($396, 8$ and $393, 4$ nm

respectively) to the continuum flux $(400, 1$ and $390, 1$ nm), that is so-called S Ca II index [2].

S Ca II index or S-index is average value over the two Ca II lines $(396, 8$ and $393, 4$ nm) normalized on the continuum flux (average value over fluxes in $400, 1$ and $390, 1$ nm).

In the following we compare the spottedness of two groups of stars: highly spotted, which have been studied at the CrAO, and lowly spotted stars from the "HK-project", which are closed to sun.

To do this we have used photometric observations data in the Stromgren "b" and "y" bands [8]; the (b + y)/2 values are very close to the standard Johnson V band. The group of "HK-project"stars with clearly distinct emission in the Ca II lines belonging to spectral classes F, G and K, which rarely overlap the sample of highly spotted stars, included only a few late K and one M star. In our investigation there are only two stars common to both groups.

In order to estimate the spottedness of the solar-type stars, we used the above mentioned photometric observations of 35 stars in the "HK-project"[8]. These 35 stars were observed over 20 years in parallel with an extension of the almost 40-year series of observations of the same stars in the H and K lines among 111 others. The modulation in the photometric light curves of the "HK-project" stars was, on the average, much lower than for the stars observed at the CrAO. This is understandable, since the stars observed at the CrAO and the "HK-project" stars belong to different samples of stars: the former are the brightest of spotted stars while the latter are characterized by exceptional chromospheric activity.

All the more interesting is a comparison of these stars from the standpoint of their simultaneous manifestation of spotting and of chromospheric and coronal activity. In our case, our observations in a single photometric band lead to an estimate for the overall spottedness of the stellar surface from the amplitude of the rotational modulation and the maximum brightness of the star corresponds to the level of the unspotted photosphere. We use an expression for the brightness of a spotted star based on the Vogt approximation [6],

$$\Delta m_\lambda = -2.5 \log(1 - (1 - \beta_\lambda)G_\lambda), \tag{1}$$

where

$$G_\lambda = ((1 - u_\lambda)I + u_\lambda J)/(I - u_\lambda/3) \tag{2}$$

Here the contrast β_λ - is the ratio of the surface brightness of a spot and the photosphere,

u_λ - is the linear limb darkening coefficient, I is the area of the projection of the spot on the plane on the chart expressed as a fraction of the star's visible disk, and J characterizes the position of the spot relative to the center of the disk. The difference in stellar magnitudes, Δm, is taken relative to the brightness level of the unspotted atmosphere. If the limb darkening is neglected, then approximately $J = 2I/3$, and we obtain the following relation for calculating the fraction of the disc occupied by spots:

$$I = (1 - 10^{-0.4\Delta m})/(1 - \beta_\lambda) \qquad (3)$$

Using Eq. (3) for for the "HK-project" stars, we obtain typical estimates for I which are numerically equal to the relative area of the stars disk occupied by spots S_{spot}. We determine the corresponding values of Δm from the photometric light curves for these stars in Ref. 8. One of the basic results of the zonal model analysis of the observations was the discovery of a distinct coupling between the temperature of the spots and absolute brightness M_V of a star (Fig. 1).

We used this relationship to determine the contrast β_λ for the other late spectral class stars, as well, in particular for the "HK-project" stars discussed here. The absolute brightness of these stars is known and have taken it from Ref. 8.

The Figure 1 shows that the dependence of the relative spots area S_{spot} on the contrast values β_λ varies negligible over $\beta_\lambda = 0.1 - 0.25$. The feasibility of estimating the spottedness of the "HK-project" stars using a simplified involving a determination of the contrasts β_λ of the stars as a function of the absolute stellar magnitude M_V has been checked by means of revers calculations of the overall area of the spots for 25 of the CrAO stars (whose spottedness is known from zonal model calculations) using Eq. (3). The greatest error in our calculations occurred in the case of the star EK Dra = HD129333, which is common to both groups of stars, where the amount of spottedness according to zonal model is a factor 1.2 - 1.3 times exceeds the value we determined. The spottedness is the same for the both methods in the case of the second star that is common to both groups of stars, BE Cet = HD1835.

We also analyzed the dependence of the area of maximum spottedness for 24 stars from "HK-project" (for these stars there appear data from ROSAT x-ray catalog) and for the 24 stars observed at the CrAO at the color index $(B-V)$. It turns out that stars with active chromospheres, with greater spottedness than the other objects in the "HK-project", belong mainly to spectral classes F,G, and, partly, K. At the other hand most of the highly spotted CrAO stars belong to spectral classes K and M. Clearly, the "HK-project"

stars whose activity level is close to that of the sun have considerably less spotting. In addition, the portion of these stars with well determined cycles of chromospheric activity, including the sun, are characterized by a still lower (by a factor of 2-3) spot area (the only exception is V2292 Oph=HD152391) compared to the other stars in the "HK-project" that were considered, whose spottedness is, in turn, a factor 2-5 times less that of stars observed at the CrAO.

Data on soft x-ray emission from the ROSAT satellite exists for 46 stars in two groups that were examined (EK Dra and BE Cet are common to the both groups). Along with determining the degree of spotting of the stars, S_{spot} (the relative area of the visible disk of the star occupied by and expressed as a percent), we analyzed the relationship between S_{spot} and L_x/L_{bol}. As note above, L_x/L_{bol} is a good index for characterizing the power of the stellar coronae.

Our calculations of the maximum spotted area for the 24 "HK-project" stars chosen for fuhrer analysis and for the 24 stars observed at the CrAO are listed in Table.

The second column in Table consists of the bolometric luminosities L_{bol}. These values of the "HK-project" stars are taken from Ref. 4 and the method employed there we used to calculate L_{bol} for the CrAO stars.

The fifth column in Table - the values of spottedness S_{spot} of stars were calculated using Eq. (3) for the "HK-project" stars (rows from 1 to 23). The values of spottedness S_{spot} of stars, observed in CrAO (rows from 24 to 46) were taken from zonal model calculations [5,9].

The values of spottedness S_{spot} of stars as plotted as a function of the ratio $\log(L_x/L_{bol})$ are shown in Fig. 2.

Here it was found for the first time that the amount of spotting varies gradually from the sun to the stars with the most powerful coronae (of the individual stars). Clearly, the gradients in the plot S_{spot} as a function of $\log(L_x/L_{bol})$ for solar-type stars and highly spotted stars are quite different. This is because of some of the highly spotted stars are already at the saturation level for x-ray emission, when a fraction 0.001 of the energy generated in the core of the star is expended in heating the coronae. Of course, the portion of the objects which are quieter than the sun were not included in our examination and should lie in the lower left hand corner of Fig. 2.

It should be noted that the method proposed here for determining the contrasts of the spots from zonal model calculations (Fig. 1), rather than from observations, does introduce some error into the determination of the amount of spottedness, but this error is small, because the contrasts vary insignificantly from star to star and only influence the result indirectly. There may also be some error in determining the brightness of stars "without spots"

because we have used photometric observations of "HK-project" stars spanning an time interval of 20 years. Thus, there is some probability that we have neglected long-period variations in the brightness over a longer or equal to 20 year time scale. Some of this discrepancy in the spottedness determination for EK Dra may be related to just factor.
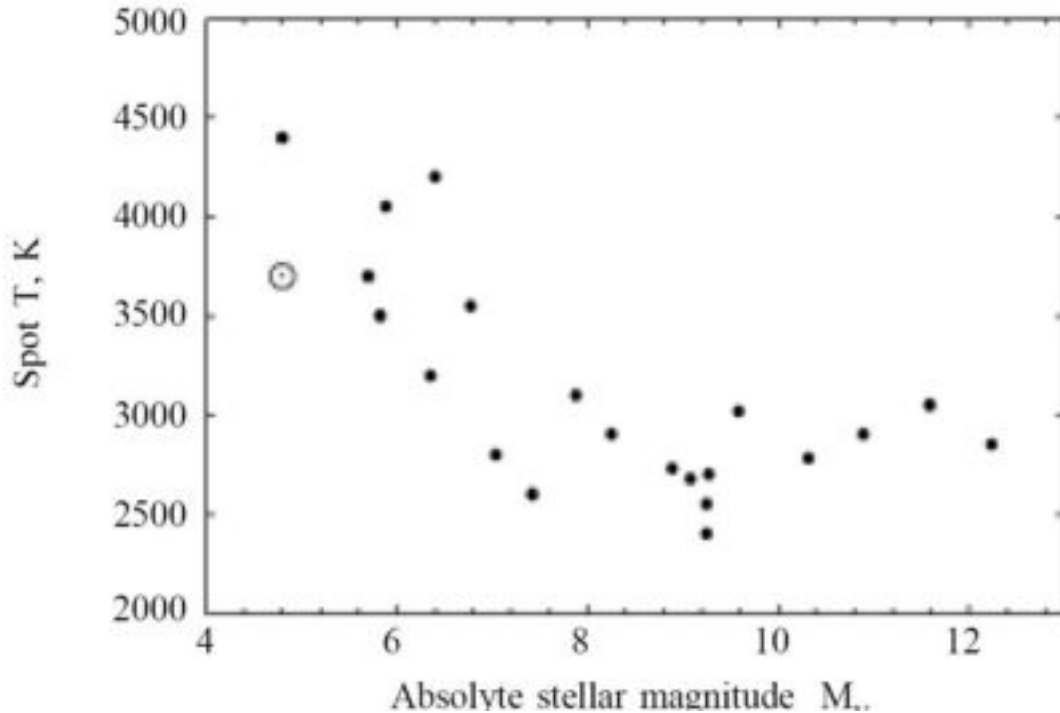

Figure 1: The temperature of the spots as a function of the absolute stellar magnitude according to zonal model calculations [6]. The symbol ⊙ denotes the sun

3. Conclusions

More than one thousand stars with processes similar to solar activity are currently known in the neighborhood of the sun. This makes it possible to investigate how the characteristics of the activity vary on going from stars with a low level of activity similar to that of the sun, to stars with soft x-ray emission with level of atmospheric activity close to maximum level of all the possible (close to saturation).

In this paper we have determined the amount of spotting of the surface of low-activity stars from the long-term variability in the optical continuum. It has been found that the calculated spotting area increases from the solar value of 0.2 % at the 11-year cycle maximum, to 1-5% for stars in the "HK-

project", and than increases sharply to 20-35 % in highly spotted stars, whose spotting areas have been determined from observations and zonal model calculations at the CrAO.
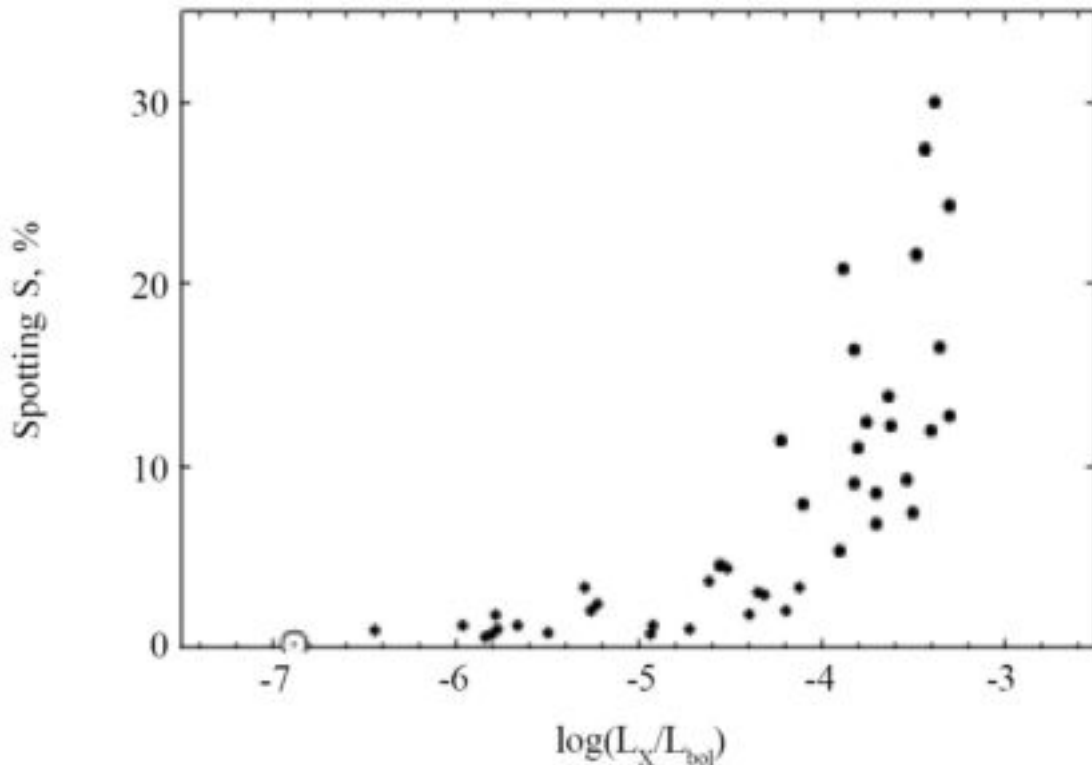

Figure 2: The area of the spotted regions as a function of the ratio $\log(L_x/L_{bol})$The symbol $\odot$ denotes the sun

A comparison of the spottedness with the relative fraction of energy expended in heating the coronae of the stars revealed a rather close coupling of S_{spot} and $lg(L_x/L_{bol})$ values. It has been suggested earlier that the deficit of radiation which is not radiated in the spots in the optical range is expended in changing the outer atmosphere of active stars of F, G, K and M spectral classes [9]. The analysis given in this paper shows that this idea is realized to the greatest extent in the coronae. Specifically, spot formation leads primarily to the formation of high temperature regions in the corona and, accordingly, to a substantial rase in the x-ray fluxes. The sun fits well into this pattern, although its level of spottedness and x-ray emission are substantially lower than in other stars with stable activity cycles.

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HD Number, Star's Name	$\log(L_x)$	$\log(L_{bol})$	$\log(L_x/L_{bol})$	S_{spot}, %
SUN	26,7	33,58	-6,88	0,20
HD81809	28,1	33,59	-5,49	0,80
HD114710,$\beta\ Com$	28,06	33,72	-5,66	1,20
HD115404	28,02	33,28	-5,26	2,00
HD160346	27,48	33,25	-5,77	1,00
HD201091, $61CygA$	27,15	33,1	-5,95	1,20
HD201092, $61CygB$	27,15	32,93	-5,78	1,80
HD149661,$V2133Oph$	28,16	33,38	-5,22	2,40
HD1835,$BECet$	28,99	33,54	-4,55	4,50
HD18256,$\rho^3\ Ari$	27,61	34,05	-6,44	0,90
HD25998,$50Per$	29,54	33,93	-4,39	1,80
HD35296,$111Tau$	29,44	33,78	-4,34	3,00
HD39587,χ^1Ori	29,08	33,69	-4,61	3,60
HD75332	29,56	33,87	-4,31	2,90
HD82885,$SWLmi$	29,3	33,42	-4,12	3,30
HD115383,$59Vir$	29,51	33,7	-4,19	2,00
HD120136,$\tau\ Boo$	28,95	33,87	-4,92	1,20
HD176095	29,0	33,93	-4,93	0,80
HD182572,$31Aql$	27,59	33,42	-5,83	0,60
HD185144, $\sigma\ Dra$	27,61	33,4	-5,79	0,70
HD190007	27,81	33,1	-5,29	3,30
HD131156, $\zeta\ Boo$	28,9	33,42	-4,52	4,40
HD157856	29,21	33,93	-7,72	1,00
HD129333, $EKDra$	30,01	33,64	-3,63	13,80
$VYAri$	30,5	33,6	-3,10	21,80
$V775Her$	30,0	33,38	-3,38	30,00
$LQHia$	29,6	33,35	-3,75	12,40
$V838Cen$	29,9	33,38	-3,48	21,60
$AGDor$	29,8	33,33	-3,53	9,20
$MSSer$	30,1	33,35	-3,25	10,00
$OUGem$	29,3	33,4	-4,10	7,90
$V833Tau$	29,8	33,1	-3,30	24,30
$EQVir$	29,4	33,1	-3,70	8,50
$BYDra$	29,6	32,95	-3,35	16,50
$CCEri$	29,5	32,93	-3,43	24,70
$DKLeo$	29,1	32,9	-3,80	11,00
$V1005Ori$	29,2	32,9	-3,70	6,80
$BFCVn$	29,0	32,82	-3,82	9,00
$DTVir$	29,2	32,82	-3,62	12,20
$AUMic$	29,5	32,8	-3,30	12,70
$FKAqr$	29,4 8	32,8	-3,40	11,90
$V1396Cyg$	28,9	32,78	-3,88	20,80
$ADLeo$	28,8	32,70	-3,90	5,30
$GTPeg$	29,2	32,7	-3,50	7,4
$VZCmi$	28,4	32,62	-4,22	11,40
$EVLac$	28,8	32,62	-3,82	16,80

REFERECES

1. R.E. Gershberg, Solar-type activity of main sequence stars, Odessa, Astroprint (2002).

2. S.L.Baliunas, R.A.Donahue, W.H.Soon, Astrophys.J. **438**, 269 (1995).

3. J.H.M.M.Schmitt, C.Liefke, Astron.Astrophys. **417**, 651 (2004).

4. E.A. Bruevich, M.M. Katsova, and D.D. Sokolov, Astron. zh. **78**, 827 (2001).

5. I.Yu. Alekseev, R.E. Gershberg, Astron. zh. **73**, 589 (1996).

6. I.Yu. Alekseev, Low-mass spotted stars, Odessa, Astroprint (2001).

7. J.T.Wright, G.W.Marcy, R.P.Butler, S.S.Vogt, Astrophys.J.Suppl.Ser. **152**, 261 (2004).

8. R.R.Radick, C.W.Lockwood, B.A.Skiff and S.L.Baliunas, Astrophys.J.Suppl.Ser. **118**, 239 (1998).

9. I.Yu. Alekseev, R.E. Gershberg, M.M. Katsova, M.A. Livshits, Astron. zh. **78**, 558 (2001).